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Joint forcing of climate warming and ENSO on a dual-cropping system

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ABSTRACT

Challenges for achieving food security with an increasing world population are stimulating many stakeholders to consider the impact of climate change on global-regional crop production. One major concern is how the covariations of climate warming and extremes (e.g., ENSO) affect agricultural systems and production. Here, a dual-cropping system in the Huaihe Plain was used as a testbed to address this issue. We found that climate warming during 1982–2013 has produced remarkable influences on the dual-cropping agricultural system. For the spring season crop (i.e., winter wheat), a significant negative effect was found with a production loss of ~6.9×10^6 tons due to an elevated T_{mean} (~2.21 °C) (r = -0.508, $p < 0.01$), which was associated with water stress. For the summer/autumn crops (i.e., rice and maize), a significant positive effect was found, but with a less substantial production gain (~1.4×10^6 tons), supposedly due to the relaxed temperature constraints (an increased T_{max} of ~1.28 °C) for high heat resistant crops (r = 0.495, $p < 0.01$). The phenophase of the crop growing period was shortened by ~7 days for the spring crop and by ~4.4 days for the summer/autumn crops with enhanced thermal conditions. Precipitation anomalies, especially those associated with ENSO turning from El Niño to La Niña, imposed an additional serious impact on the dual-cropping system through decreased precipitation in the spring and increased precipitation in the summer/autumn. Potential impacts for the future could be derived from intensification of water and heat stresses, as well as the climate extremes (e.g., ENSO and AAO).

1. Introduction

Provisioning the necessary quantity of agricultural crops to meet the demand of the massive world population (~7 billion people at current, and ~9 billion by 2050) is becoming an unprecedented challenge because of rapid changes in global climate and variability (Godfray et al., 2010; Lobell et al., 2011). In the past, the hurdles of providing food for the world's growing population have been met with technological advances such as those seen during the Green Revolution that significantly increased global crop production through the development of high-yielding varieties of cereal grains, modernization of management techniques, and the use of synthetic fertilizers and pesticides (Farmer, 1986; Jain, 2010; Zeng et al., 2014). However, the yield growth rate appears to have stagnated in recent decades (Alston et al., 2009; Chen et al., 2014). Climate warming, particularly from the 1980's to the present, as well as its new norms of spatial and temporal distributions, have been suggested as imposing inevitable consequences on the production of staple crops at the global-regional scale (Lobell and Field, 2007).

Studies by model simulation and experimental analysis indicated that increasing temperature and precipitation variability will have profound consequences on the production of staple crops (e.g., wheat, rice, maize, and soybean, etc.) (Asseng et al., 2015; Knox et al., 2012; Lobell and Field, 2007; Schlenker and Roberts, 2009; Schmidhuber and Tubiello, 2007). Wide-spread threats may include out-tolerance heat stress (Deryng et al., 2014; Mishra and Cherkauer, 2010), elevated water deficits (Asseng et al., 2004; Zhang et al., 2004), and altered phenological phases (Alexandrov and Hoogenboom, 2000). These impacts are not only due directly to warming trends (Goldblum, 2009), but also co-vary with the occurrence and magnitude of climate extremes, regional/global atmospheric oscillations (e.g., ENSO referring to the year-to-year variations in atmospheric circulation occurring across the equatorial Pacific Ocean) (Garnett and Khandekar, 1992; Hansen et al., 1998; Holton et al., 1989), as well as advancement in agricultural technologies and management practices (Tilman et al., 2002). At decadal and regional scales, ENSO, which has resulted in significant increases/decreases in precipitation in recent decades, appeared to be responsible for changes in crop production for many regions (Adams et al., 2003; Legler et al., 1999). Given the widely managed multiple cropping systems, these confounding effects on crop production can be complicated by seasonal variations in climate (Lobell and Burke, 2008; Matthews et al., 1997). A critical issue is whether the

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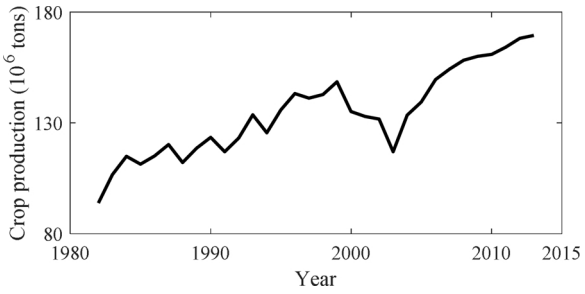

Fig. 1. The 32-year (1982–2013) changes in crop production in the Huaihe Plain (HP) of China.

impact of climate warming associated with elevated water deficits on crop production can be intensified or mitigated by the increased/decreased precipitation induced by ENSO. Unfortunately, the joint or independent effects of climate warming and variability have not been effectively studied in the literature, partially due to the lack of available data (i.e., long-term, high temporal frequency data for monitoring crop production) except for yield for sound analysis and modeling. Yet this knowledge and trajectory capability are crucial for landowners for timely adjustments of cropping strategy, as well as location-specific adaptive management actions (Adams et al., 2003; Morton et al., 2017; Porter and Semenov, 2005).

Using the Huaihe Plain (HP) of China as our testbed, where annual crop production has increased by 81% (93.81×10^6 to 169.45×10^6 tons) over the past 32 years (1982–2013) with substantial interannual variations (Fig. 1), we performed a systematic analysis by combining long-term recorded data to explore the combined impact of multiple climate factors on a dual-cropping system. Specifically, we address the following three questions: 1) How did the dual-cropping crops across the HP respond to climate warming over the past 32 years? 2) Would the changes in phenophase associated with climate warming have additional contributions to crop production? and 3) What are the joint and independent influences on crop production from climate warming and ENSO? Here, we hypothesize that ENSO, as well as the Antarctic Oscillation (AAO) and the Arctic Oscillation (AO) are the major climatic events responding for the interannual changes in crop production across the HP. The AAO is a low-frequency mode of climate variability in the southern hemisphere. While in its negative phase, the westerly wind belt moves towards the equator and can influence local climate (Sun et al., 2009). In most cases, ENSO and AAO affect crop production by altering precipitation regime (Barlow et al., 2002). The AO is characterized by non-seasonal sea-level pressure anomalies of one sign in the Arctic with the opposite anomalies centered around 37–45 °N, which can lead to extremely low-temperature stress for crop growth (Higgins et al., 2002).

2. Materials and methods

2.1. Study area

Located in the eastern region of China (110–122 °E; 29–38 °N), the HP is a major agricultural base for China. It covers 0.56×10^6 km^2 in four provinces (Henan, Shandong, Anhui and Jiangsu) (Fig. 2a) and was the home to 340 million people in 2013. Climatically, the HP falls within the transitional zone from the subtropical to the temperate zone (Fig. 2b) in the Eurasian continent. Its climate is characterized by continental monsoons, with an annual average temperature of ~14.7 °C, a maximum of 30.6 °C in August, and a minimum of -2.6 °C in January. The frost-free period varies from 200 to 240 days. Evapotranspiration (ET) is greater in the north than in the south, ranging between 850 mm and 870 mm. The annual precipitation varies from 650 mm to 1250 mm. The plain has an elevation range of 200–500 m (Fig. 2c) and is dominated by semi-hydromorphic soil. The Huaihe River – one of seven major rivers in China – runs through the plain and provides a rich water supply for irrigation. Other than the mountains where forests dominate (15%), more than 72% of the HP (0.4×10^6 km^2) is cultivated for crops (Fig. 2d). Owing to its long growing season and rich water resource, the dual-cropping system has been practiced for centuries with a rotation of winter wheat in the spring season (March-May) and rice (or maize) in the summer/autumn season (June-August). The portion of these three crops to the total crop production of the region steadily increased from 80.2% in 1982 to 95.4% in 2013. During our study period, new crop cultivars of wheat, rice, and maize were often irregularly released to the farmers by the government (Liu et al., 2010). The use of chemical fertilizer in the HP has sharply increased by ~360% since the 1980s.

2.2. Data sources

This study used several sources for crop production, remote sensing images, climate, and climate oscillation data (Table 1). The data for annual winter wheat, rice, and maize production during 1982–2013 for the four provinces were collected from the Chinese Statistics Yearbook (http://www.stats.gov.cn/tjsj/ndsj/). Crop phenological phases and photosynthetic activity were measured by the Global Inventory Modeling and Mapping Studies NDVI (GIMMS-NDVI3g) (http://ecocast.arc.nasa.gov/data/pub/gimms/). GIMMS-NDVI3g is a 15-day maximum-value composite (MVC) NDVI from July 1981 to December 2013 at 0.08° × 0.08° (~ 8 km) resolution.

Meteorological datasets during 1982–2013, including daily mean temperature (°C), daily maximum temperature (°C), daily minimum temperature (°C), daily sunshine hours (h/day), and daily precipitation (mm), from the 78 meteorological stations within the HP (Fig. 2c) were downloaded from the Climatic Data Center, National Meteorological Information Center, China Meteorological Administration (http://data.cma.cn/). Photosynthetically Active Radiation (PAR) is calculated as 48% of solar radiation (MJ/m^2), which was calculated from sunshine hours following the protocols of the Food and Agriculture Organization (FAO) (Allen et al., 2005; Zotarelli et al., 2010). The Palmer drought severity index (PDSI), which combines the information from both temperature and precipitation (Palmer, 1965), was used to analyze water stress on crop growth. PDSI datasets at 0.5°× 0.5° resolution from 1982 through 2013 were obtained from ftp://ftp.ntsg.umt.edu/pub/NPP_Science_2010/PDSI/. The Oceanic Niño Index (ONI), defined as those above a +0.5°anomaly for El Niño events and below a -0.5° anomaly for La Niña, the AAO index, and AO index were used to explore the potential impact of climate extremes on crop production for the HP (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/climwx.shtml).

2.3. Delineating phenophases

Agriculture in the HP is characterized by a dual-cropping system involving spring and summer/autumn season crops (Fig. 3). The spring season crop is planted during the previous autumn and harvested the following May. Accordingly, its phenophase, including greenup and maturity, are delineated based on time series logistic models of NDVI (Zhang et al., 2003). The summer/autumn crops are planted after the wheat is harvested, with the date of planting and maturity directly delineated by the breakpoint in the trajectory of the NDVI.

2.4. Quantifying the climatic effects

To explore the effects of climate on crop production, we used a detrending method to model the anomalous changes in crop photosynthetic activity, which was measured by time series NDVI (Sakamoto et al., 2011; Wang et al., 2016). This method is expected to exclude the potentially confounding effects from non-climatic factors such as modern agricultural technologies and management practices (Lobell

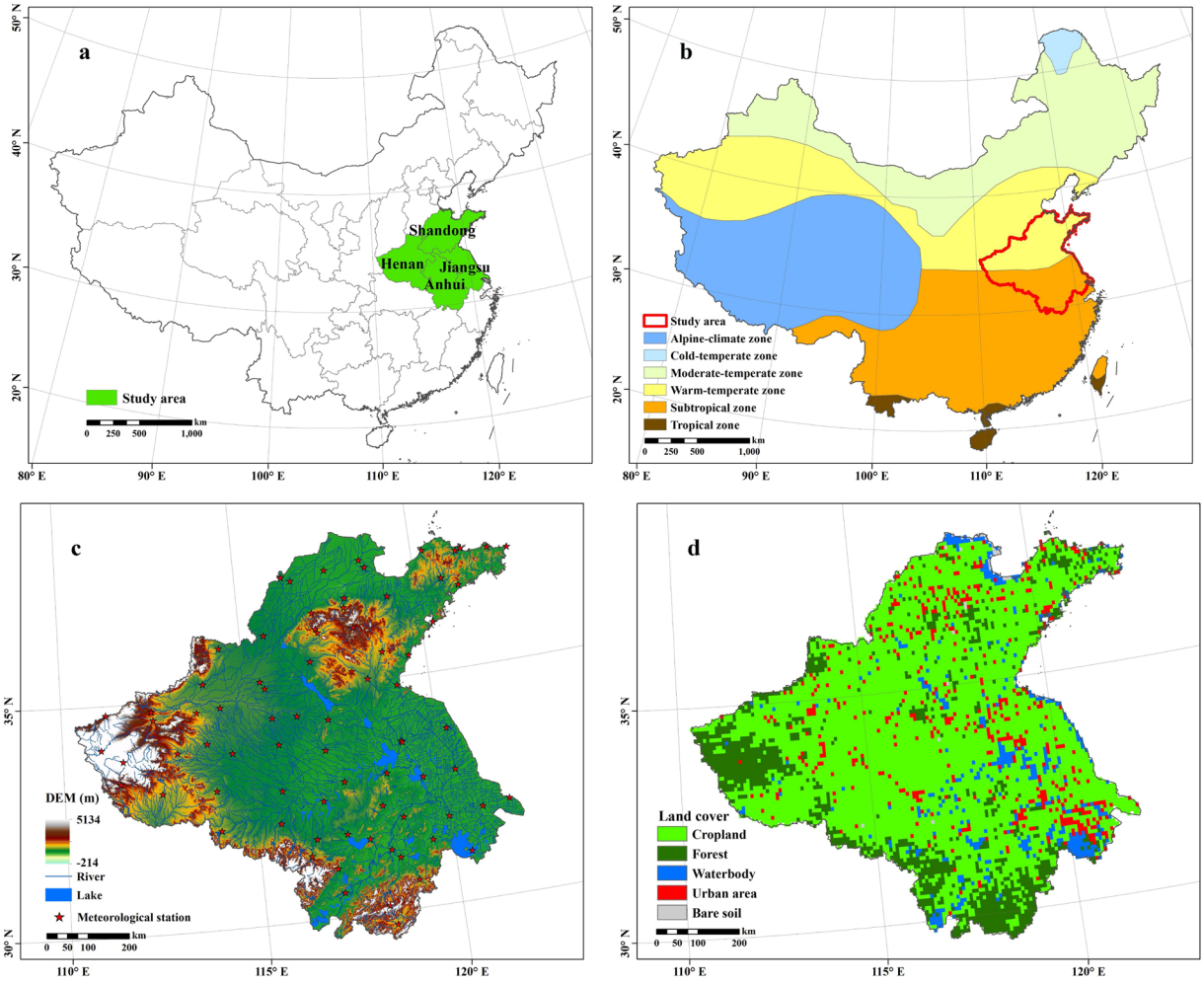

Fig. 2. The HP of China. (a) administrative areas, (b) climate zones, (c) terrain, water system, and distribution of meteorological stations, and (d) land cover in 2010.

Table 1
Summary of data for this study. NDVI is the Normalized Difference Vegetation Index; PAR is the Photosynthetically Active Radiation; T_{mean} is the mean temperature; T_{max} is the maximum temperature; T_{min} is the minimum temperature; T_{dtr} is the diurnal temperature; Precip is the total precipitation during the crop growing period; ONI is the Oceanic Niño Index; AAO is the Antarctic Oscillation index; AO is the Arctic Oscillation index; GIMMS-NDVI3g is the Global Inventory Modeling and Mapping Studies NDVI; NOAA is the National Oceanic and Atmospheric Administration.

Category	Variables	Temporal resolution	Spatial resolution	Data source
Statistical data	Crop production: wheat, maize, and rice	Yearly	Provincial scale	Statistical Yearbook
Remote sensing data	NDVI	15-day	0.08° × 0.08°	GIMMS-NDVI3g
Climate data	PAR, T_{mean}, T_{max}, T_{min}, T_{dtr}, and Precip	Daily	Site scale	Meteorological stations
Drought index	PDSI	Monthly	0.5° × 0.5°	Reanalysis data
Climate oscillation	ONI, AAO, and AO	Monthly	Global scale	NOAA

and Field, 2007; Lobell et al., 2011). We then modeled the quantitative relationships between the detrended NDVI and each climatic variable through correlation analysis, including PAR, the average daily mean temperature (T_{mean}), the average daily maximum temperature (T_{max}), the average daily minimum temperature (T_{min}), the average daily diurnal temperature (T_{dtr}), the average PDSI, and the precipitation during the growing period. It should be noted that the calculations of climatic variables were based on phenophase (e.g., from greenup to maturity for the spring crop, and from planting to maturity for the summer/autumn crops). To further explore the complex direct/in-direction interactions among the dependent and independent variables, partial least squares structural equation modeling (PLS-SEM; Hair et al., 2011) – a method allowing estimation of complex cause-effect relationships with multiple dependent variables – was employed to explore the joint effects from thermal (i.e., PAR, T_{mean}, T_{max}, T_{min} and T_{dir}) and water (precipitation and PDSI) perspectives. We avoided using the conventional multi-variable time series regression to separate the contribution of each of these climatic variables as they have a strong interdependency that violates the assumption for method application (i.e., independence). Meanwhile, application of PLS-SEM helps to diagnose the potential covariations and significant correlations among the climatic variables (Fan et al., 2016).

3. Results

3.1. Changes in NDVI

The onset of greenup for the spring crop occurred in February through the first 15 days of March, with maturity reached in the first 15 days of May, while the planting of the summer/autumn crops occurred

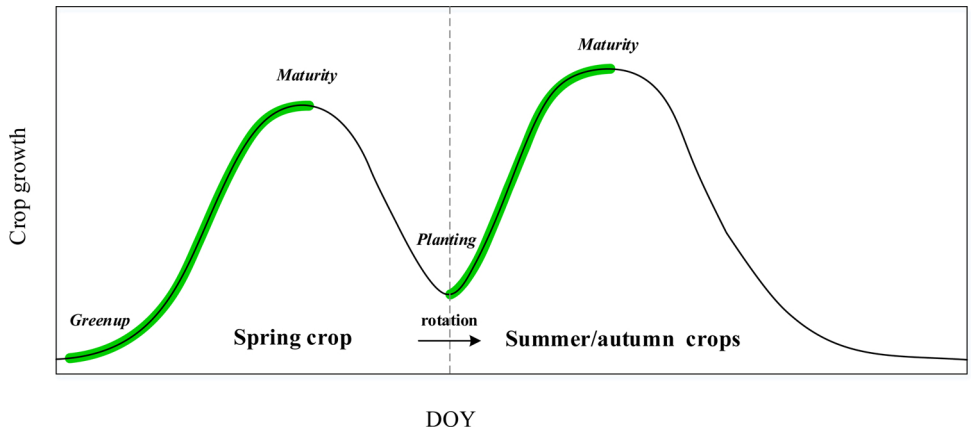

Fig. 3. A hypothetical trajectory of vegetation index values for a dual-cropping system.

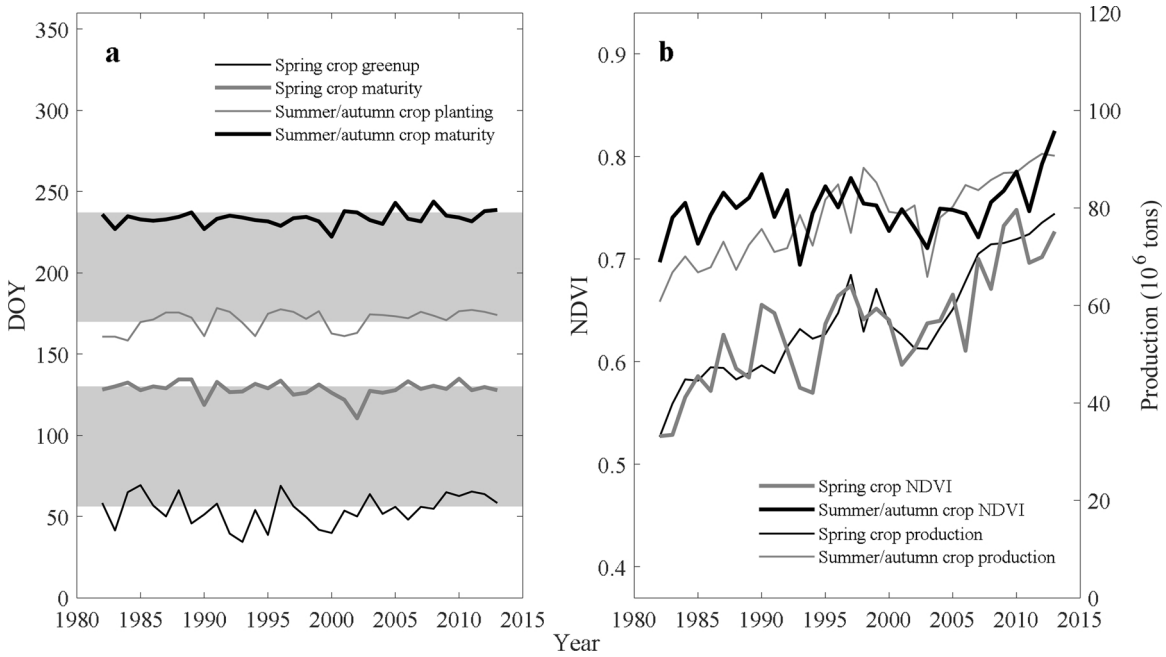

Fig. 4. (a) the 32-year changes in phenological phases for the dual-cropping system in the HP, and (b) changes in maximum NDVI of the mature phase and corresponding production for spring and summer/autumn crops.

during June, with maturity reached in the last 15 days of August (Fig. 4a). The changes in NDVI matched well with crop production (Fig. 4b), with a correlation coefficient (r) of 0.857 ($p < 0.001$) between NDVI and spring crop production and 0.491 ($p = 0.004$) between NDVI and summer/autumn crop production. The lower r for the latter is mainly attributed to the inclusion of multiple crops (e.g., rice, maize, etc.), while winter wheat is the exclusive spring crop. More importantly, the rates of increase in production for spring and summer/autumn crops are also tightly coupled by the changes in NDVI. Between 1982 and 2013, the NDVI for the spring crop increased from 0.53 to 0.75 (42%) and from 0.7 to 0.82 (17%) for the summer/autumn crops. These increases in the NDVI are comparable to a 138% and 49% change in production, respectively, for the spring (33.08×10^6 to 78.79×10^6 tons) and summer/autumn crops (60.73×10^6 to 90.66×10^6 tons) over the 1982–2013 study period. Interestingly, the sharp decreases in NDVI for both the spring and summer/autumn crops were the mirror reflections of remarkable decreases in production during 1997–2003.

3.2. Climatic effects

Both the correlation matrix (Table 2) and path coefficient (r_p) of PLS-SEM (Fig. 5) showed that the responses of crop growing activities to the climatic changes were different between the two dual-cropping crops. For the spring crop, the variables reflecting the thermal conditions (i.e. PAR, T_{mean}, T_{max}, T_{min}, and T_{dtr}) played a negative role for NDVI (r=-0.508-0.016; r_p=-0.481, $p < 0.001$), whereas those reflecting the water conditions (i.e., precipitation and PDSI) had a positive relationship with NDVI (r = 0.134-0.236; r_p = 0.133). Among all explored climatic variables, T_{mean} appeared to have the most significant negative effect on crop growth (r=-0.508, p = 0.003; r_p = 0.998, $p < 0.001$), while PDSI showed more significant positive effects than precipitation (r_p = 0.930, p = 0.004 vs r_p = 0.760, p = 0.026) (Fig. 5a). As for the summer/autumn crop, all factors representing the thermal conditions played a significant positive role for NDVI (r = 0.370-0.617, $p < 0.010$; r_p = 0.457, p = 0.010), whereas increased water supplies played a negative role (r=-0.416-0.027; r_p=-0.126). Among all of the climatic factors, T_{max} showed the most significant positive effect on NDVI (r = 0.495, p = 0.004; r_p = 0.983, p = 0.004), while precipitation showed a significantly constraining effect (r=-0.416, p = 0.018; r_p = 0.998, $p < 0.001$) (Fig. 5b). This evidence indicates that climate warming over the past 32 years has already led to remarkable influences on crop production for the dual-cropping agricultural system.

Table 2
Correlation (*r*) matrix among climatic variables as well as detrended NDVI for spring and summer/autumn crops. Dark gray represents a negative effect, while light gray represents a positive effect. Statistically significant *p*-values are denoted as *** < 0.001, ** < 0.01, and * < 0.05.

		PAR	T_{mean}	T_{max}	T_{min}	T_{dtr}	Precip	PDSI
Spring crop	T_{mean}	0.379*						
	T_{max}	0.618***	0.951***					
	T_{min}	-0.070	0.887***	0.708***				
	T_{dtr}	0.946***	0.450**	0.701***	-0.007			
	Precip	-0.782***	-0.196	-0.410*	0.178	-0.760***		
	PDSI	-0.208	-0.142	-0.206	0.015	-0.307	0.467**	
	NDVI	**-0.016**	**-0.508****	**-0.466****	**-0.498****	**-0.157**	**0.134**	**0.236**
Summer/autumn crops	T_{mean}	0.800***						
	T_{max}	0.866***	0.984***					
	T_{min}	0.628***	0.962***	0.903***				
	T_{dtr}	0.856***	0.550**	0.686***	0.308			
	Precip	-0.728***	-0.397*	-0.497**	-0.193	-0.776***		
	PDSI	-0.149	0.076	0.027	0.180	-0.246	0.410*	
	NDVI	**0.617*****	**0.459****	**0.495****	**0.370****	**0.470****	**-0.416***	**-0.027**

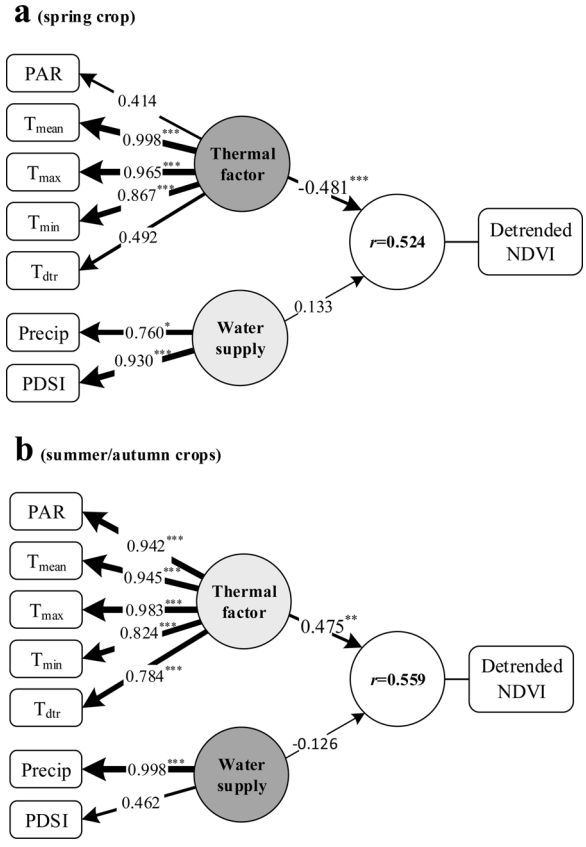

Fig. 5. Partial least square structural equation modeling (PLS-SEM) of climatic effects on NDVI anomaly for (a) spring crop, and (b) summer/autumn crops. The PLS-SEM particularly considered a synergistic effect of thermal factor (i.e., PAR, T_{mean}, T_{max}, T_{min} and T_{dir}) and water supply (precipitation and PDSI) on crop production. Dark gray represents a negative effect, while light gray represents a positive effect. Arrow width corresponds to the strength of the path coefficient. Statistically significant *p*-values are denoted as *** < 0.001, ** < 0.01, and * < 0.05.

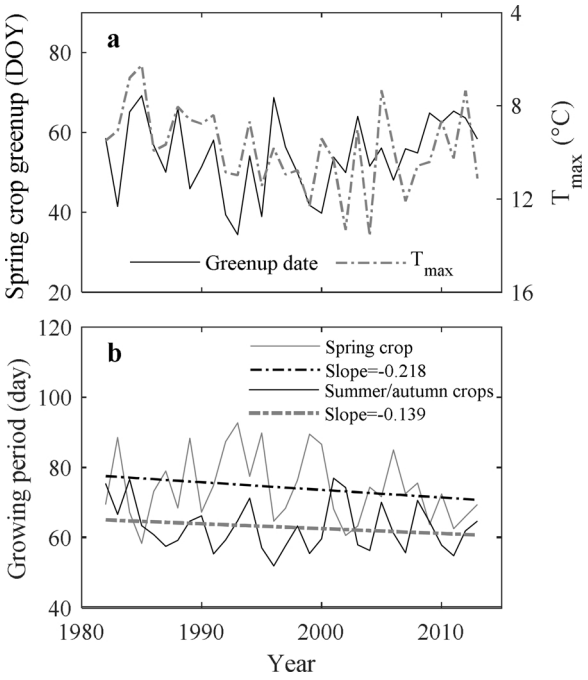

Fig. 6. Changes of phenological phases for the dual-cropping system from 1982 through 2013. (a) variations of the date (day of year, DOY) of greenup onset for the spring crop and the maximum temperature (T_{max}) in the period of greenup, (b) trends of growing period for the spring and summer/autumn crops.

3.3. Phenological changes

The date of greenup onset for the spring crop was advanced by 13.5 days from 1982 through 2000. However, it was delayed by 16.8 days from 2000 through 2013 (Fig. 6a). Thermal conditions appeared partly responsible for the changes in the date of greenup onset for the spring crop (r = -0.246-0.448, p = 0.175-0.010; r_p = -0.489, $p < 0.001$) (Table 3), with T_{max} playing the most important role in influencing greenup for the spring crop (r = -0.448, p = 0.010; r_p = 0.962, $p < 0.001$). Additionally, the growing period for the spring crop (i.e., from greenup to maturity) was shortened by ~7 days by 2013, while the growing period for the summer/autumn crops was shortened by ~4.4

Table 3
Correlation coefficients (r) and path coefficients (r_p) of PLS-SEM, as well as statistically significant p-values between thermal factors (TF, involving in PAR, T_{mean}, T_{max}, T_{min} and T_{dtr}), water supply (WS, involving in precipitation and PDSI) and date of spring crop greenup in unit of DOY.

Climate vs Greenup	r	p	Pathway	r_p	p	Pathway	r_p	p
PAR vs DOY	−0.443	0.011	PAR→TF	0.693	0.000	TF →DOY	−0.489	0.000
T_{mean} vs DOY	−0.377	0.034	T_{mean}→TF	0.832	0.000			
T_{max} vs DOY	−0.448	0.010	T_{max}→TF	0.962	0.000			
T_{min} vs DOY	−0.246	0.175	T_{min}→TF	0.578	0.016			
T_{dtr} vs DOY	−0.411	0.019	T_{dtr}→TF	0.826	0.000			
Precip vs DOY	0.045	0.808	Precip→WS	0.245	0.628	WS →DOY	0.048	0.806
PDSI vs DOY	0.172	0.348	PDSI→WS	0.968	0.039			

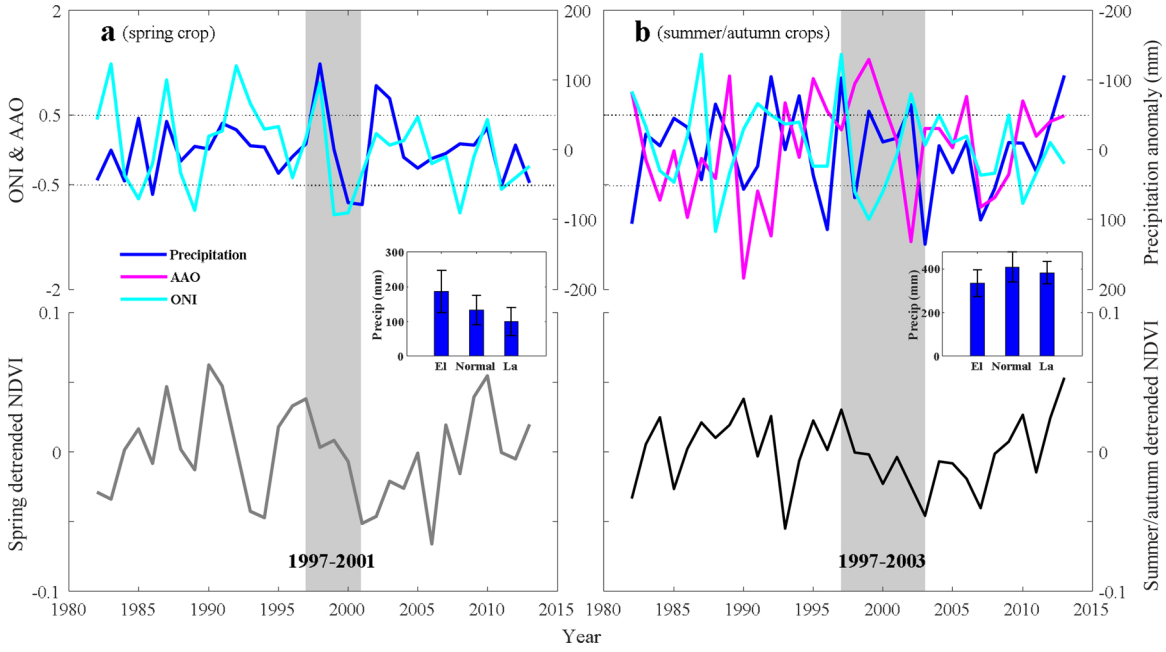

Fig. 7. Interannual variations of Oceanic Niño Index (ONI) and Antarctic Oscillation (AAO), as well as precipitation and NDVI anomalies for the dual-cropping system. The inserted figures represent the changes of precipitation in response to periods of atmospheric circulation from El Niño (i.e., ONI > = 0.5) to normal (ONI between -0.5-0.5), and then to La Niña (ONI < = -0.5). The gray bars represent NDVI anomalies associated with precipitation anomalies for both spring and summer/autumn crops during ~1997–2003. (a) spring season, and (b) summer/autumn season.

days (Fig. 6b).

3.4. Impact of ENSO on crop production

Precipitation anomalies in the spring and summer/autumn seasons played a divergent role in crop production (Table 2 and Fig. 5). For the HP, especially since 1990, a strong connection was found between precipitation anomalies and ENSO in both the spring season (r = 0.523, p = 0.009) (Fig. 7a) and summer/autumn season (r= -0.349, p = 0.094) (Fig. 7b). However, the ENSO on the HP produced different changes in precipitation for spring and summer/autumn seasons. The worst situation was found when ENSO turned from El Niño (at or above a 0.5 anomaly) to La Niña (at or below a -0.5 anomaly); precipitation decreased from 187.41 mm to 100.03 mm in the spring season but increased from 334.38 mm to 383.24 mm in the summer/autumn season. As a result, there was a simultaneously dramatic decrease in crop production within the statistical data and NDVI for both spring and summer/autumn crops during 1997–2003 (Fig. 4b). For the summer/autumn growing season, the AAO appeared to be another factor responsible for the decrease in summer/autumn crop production during 1997–2003 through taking over the precipitation anomaly (Fig. 7b).

4. Discussion

Several studies have suggested that global climate change in past decades has already slowed crop production for most crop-growing regions (Asseng et al., 2015; Pinke and Lövei, 2017). The predominantly highlighted issue has been the impact of elevated temperature on crop production in the past and future (Pinke and Lövei, 2017; Schauberger et al., 2017; Schimel, 2006; Tao et al., 2016). Compared with previous reports, the dual-cropping system in the HP showed variable responses to climate warming. For the spring season crop, we found a consistent significant negative relationship between T_{mean} and detrended NDVI (R^2 = 0.258, p = 0.003) (Fig. 8a and 8b). Given an explanation of 73.4% for NDVI to production (R^2 = 0.734, p < 0.001), we estimated that climate warming has reduced winter wheat production by ~6.9 × 10^6 tons because of increased T_{mean} (~2.21 °C from 1982 to 2013). This also prompts a clear warning that future winter wheat production in the HP might be confronted by a greater challenge given the ongoing climate warming predicted by most studies (Liu et al., 2015; Pachauri et al., 2014; Pinke and Lövei, 2017). As for the summer/autumn crops in the HP (1.14:1 for maize:rice), we found a significant positive relationship between T_{max} and detrended NDVI (R^2 = 0.245, p = 0.004) (Fig. 8c and 8d), with an estimated increment of ~1.4 × 10^6 tons for maize and rice due to climate warming (i.e., an increased T_{max} of 1.28 °C from 1982 to 2013). We speculate that climate warming has probably relaxed temperature constraints for the high heat resistant crops (Lobell et al., 2011), such as maize (a C4 plant) (Tao et al., 2016). Schlenker and Roberts (2009) reported that the response of maize is non-linear, with an optimal temperature of

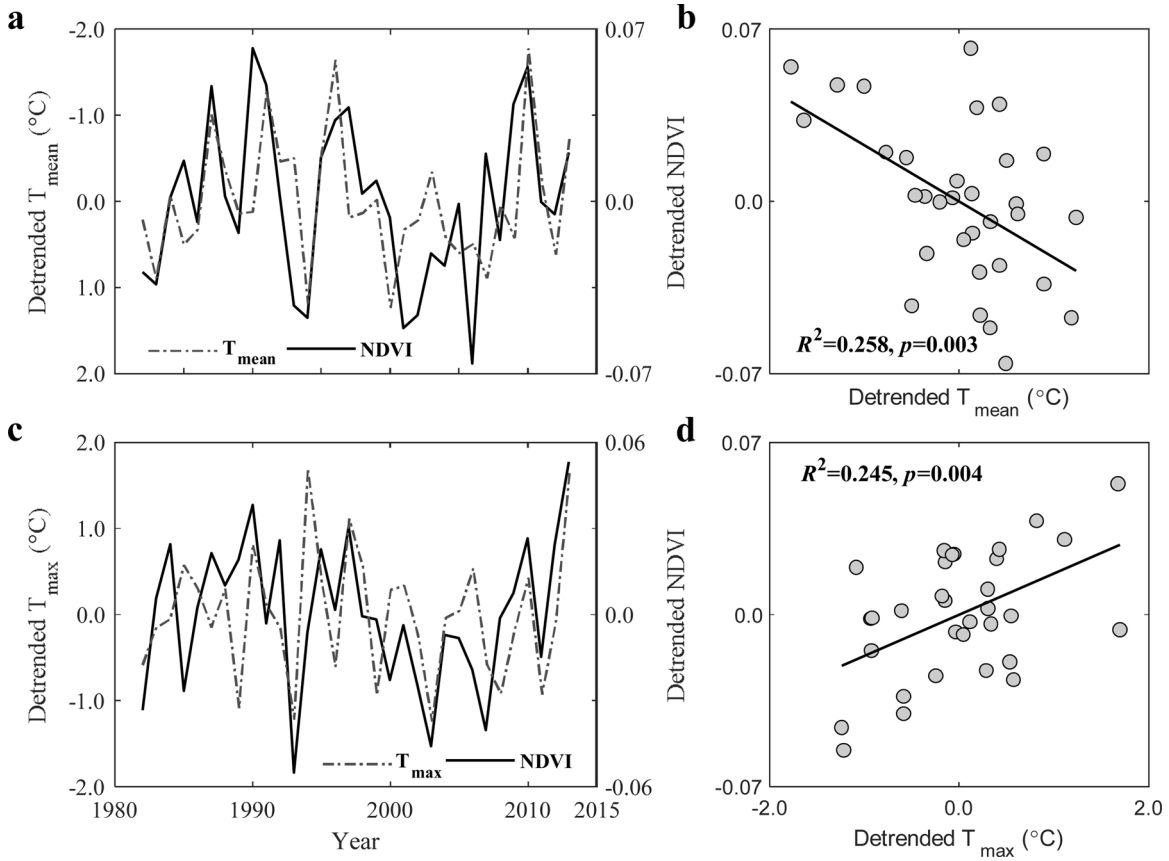

Fig. 8. Relationship between detrended NDVI and temperature for a dual-cropping system in the HP. (a) interannual changes in detrended NDVI and T_{mean} from 1982 to 2013 for spring crop, (b) relationship between detrended NDVI and T_{mean} for spring crop, (c) interannual changes in detrended NDVI and T_{max} from 1982 to 2013 for summer/autumn crops, and (d) relationship between detrended NDVI and T_{max} for summer/autumn crops.

29 °C. Crop yields would decrease sharply above this threshold. However, Zhao et al. (2016) found no evidence in Southeast China to support this non-linear effect, while reporting a large positive effect on its yield from climate warming. Here, we also witnessed a significant positive relationship between the T_{max} (which reached 33.11 °C in 2013), increases in NDVI ($r = 0.495$, $p = 0.004$) and yield ($r = 0.303$, $p = 0.098$). This provides a practical evidence that the leaf photosynthesis rate of maize has an extra highly optimum temperature (Edwards and Baker, 1993; Oberhuber and Edwards, 1993). As for rice, whose optimum temperature for maximum grain formation and yield was suggested as about 25 °C, grain yield would be significantly reduced since temperature increased above 25 °C (Edwards and Baker, 1993). However, based on crop statistical data, this situation did not occur in the HP. The reason might be attributed to the development of modern breeding techniques as well as optimization of agricultural management (Liu et al., 2010). However, temperature increases are likely to be ongoing in the future, suggesting that the risk of heat stress for these crops remains in existence (Ortiz et al., 2008).

The extremely low-temperatures are also suggested to be detrimental to crop growth and production (Hatfield et al., 2011). Over the past 32 years, four instances of extremely low-temperatures (i.e., 1987, 1991, 1996 and 2010), associated with strong cold air induced by the AO for the spring crop, were identified (Fig. 9a). However, we did not find the low-temperature stress on the crop growth in the HP from behaviors in NDVI, even though the T_{max} in the growing season (20.4 ± 4.2 °C) was still less than the optimal threshold for wheat (26 °C) (Hodges and Ritchie, 1991). Instead, a close positive relationship between NDVI and PDSI were found (Fig. 9b). This might be due to the effects of the water deficit linking with rising temperature (Mishra and Cherkauer, 2010; Paulsen, 1994; Wang et al., 2016). It implies that the impact of climate warming on the spring crop might have evolved from an increase in soil water deficits through directly increasing soil evaporation and crop transpiration (Hatfield et al., 2011). In contrast, a negative relationship between NDVI and precipitation was found for summer/autumn crops (Table 2 and Fig. 5b). The main reason is that increases in precipitation can remarkably reduce PAR that in turn suppresses crop photosynthesis (Fig. 9c). For both the spring crop and summer/autumn crops, the situation can be periodically intensified by climate oscillations from ENSO and AAO, which regularly reduce the precipitation in spring season and increase the precipitation in the summer/autumn season (Iizumi et al., 2014; Liu et al., 2014; Ropelewski and Halpert, 1987; Timmermann et al., 1999; Ying et al., 2015).

The significant increases in crop production in the HP might be mostly attributed to modern agricultural technologies and management practices (Jain, 2010). However, gains from technological advancements and new management practices will likely mislead farmers to neglect the impact of climate change, but overuse management practices (Zalidis et al., 2002), such as excessively using chemical fertilizer that will elevate soil and water pollution. Regrettably, due to the limitations in data (e.g., experimental field and survey data), the contributions of chemical fertilization as well as other agricultural technologies are unexplored in this study. In addition, in this study we analyzed just two season crops (winter wheat for the spring season and a combination of rice and maize for the summer/autumn season). For future studies, we would focus on the co-effects of multiple factors on the individual crop as well as their spatial discrepancies. Finally, as a suggestion for policy-makers and farmers, improving irrigation practices (Chen et al., 2014; Lobell et al., 2011; Pittelkow et al., 2015) as well as reducing agricultural pollution (Iizumi et al., 2014; Sun et al.,

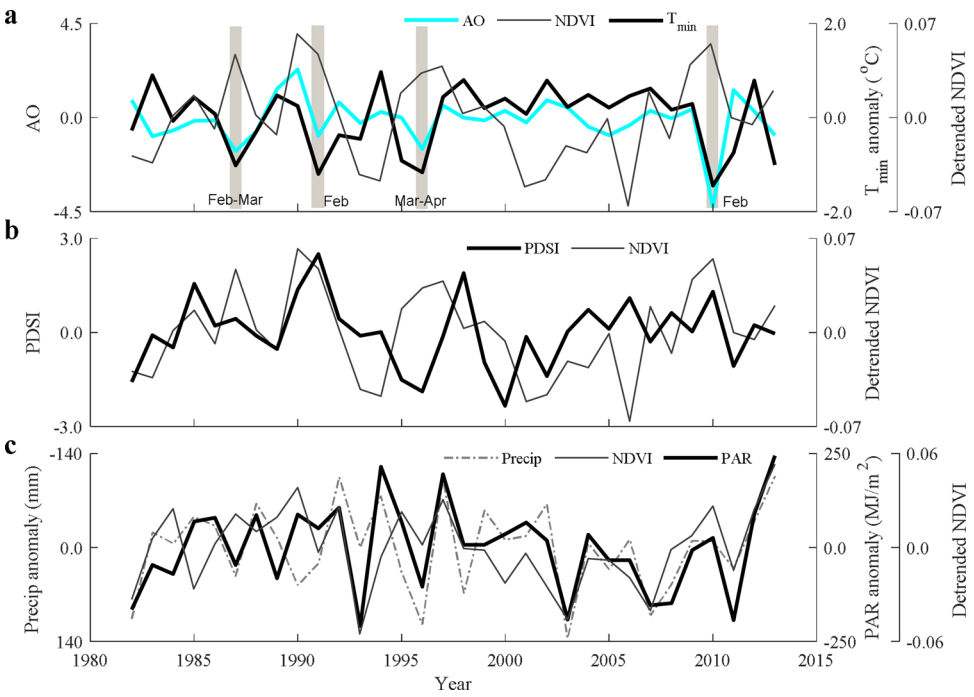

Fig. 9. Interannual variations of Arctic Oscillation (AO), climatic variables and detrended NDVI for a dual-cropping system in the HP. (a) inter-annual changes in AO, T_{min} and detrended NDVI. The gray bars represent extreme T_{min} associated with the effect of AO events in the spring season. (b) inter-annual changes in PDSI and detrended NDVI, and (c) inter-annual changes in precipitation and PAR, as well as detrended NDVI in the summer/autumn season.

2012) would be a sustainable pathway for mitigating the impact of climate change on crop production. Lessons learned from this study would lend solid scientific evidences for future adaptive actions, including policies and alternative practices.

5. Conclusions

Climate change during 1982–2013 ha s produced remarkable influences on the dual-cropping agricultural system in the Huaihe Plain (HP) of China. Three major findings of this study include:

(1) Climate warming played a significant negative role in crop production in the spring season, with a production loss of ˜6.9 × 10^6 tons over the 32-year period. At present, a potential impact could arise from intensified water stress because of enhanced thermal conditions. For the summer/autumn seasons, a positive response was found with a more minor increase in production (˜1.4 × 10^6 tons). Potential impact for the future could include out-tolerance heat stress, although the heat tolerances of rice and maize were found to be much higher than those in previous reports.
(2) Climate warming significantly affected crop growing phenophase (e.g., greenup and growing period). As a result, crop production was accelerated by shortening the crop growing period (e.g., 7 days for the spring and 4.4 days for summer/autumn crops in the HP from 1982 to 2013).
(3) Precipitation anomalies associated with the El Niño-Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO) imposed an additional serious impact on both the spring and summer/autumn crops through decreased precipitation in the spring season and increased precipitation in the summer/autumn season. The remarkable decreases in production during the ˜1997–2003 period for both the spring and summer/autumn crops were most likely due to the negative impacts of ENSO and AAO.

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